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Clinical evaluation of synthetic aperture sequential beamforming

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ABSTRACT

In this study clinically relevant ultrasound images generated with synthetic aperture sequential beamforming (SASB) is compared to images generated with a conventional technique. The advantage of SASB is the ability to produce high resolution ultrasound images with a high frame rate and at the same time massively reduce the amount of generated data. SASB was implemented in a system consisting of a conventional ultrasound scanner connected to a PC via a research interface. This setup enables simultaneous recording with both SASB and conventional technique. Eighteen volunteers were ultrasound scanned abdominally, and 84 sequence pairs were recorded. Each sequence pair consists of two simultaneous recordings of the same anatomical location with SASB and conventional B-mode imaging. The images were evaluated in terms of spatial resolution, contrast, unwanted artifacts, and penetration depth of the ultrasound beam. Five ultrasound experts (radiologists) evaluated the sequence pairs in a side-by-side comparison, and the results show that image quality using SASB was better than conventional B-mode imaging. 73 % of the evaluations favored SASB, and a probability of 70 % was calculated for a new radiologist to prefer SASB over conventional imaging, if a new sequence was recorded. There was no significant difference in penetration depth.

Keywords: Synthetic aperture sequential beamforming, ultrasound imaging, clinical evaluation, clinical demonstration.

1. INTRODUCTION

In virtually all surgical and internal medicine specialties, ultrasound scanning is a very important diagnostic tool. It is being used for e.g. prenatal screening, diagnosis and assessment of cardiovascular disease, numerous cancer types, musculoskeletal disease, and traumatic organ damage. Besides for the visual diagnosing, ultrasound is being used for guidance when a physician is performing a needle biopsy, or placing a drainage tube in e.g. an abscess or other cavity. Different kinds of ultrasound scannings are performed by physicians at all levels, radiographers, nurses, and midwives. Every improvement will therefore benefit large groups of patients and healthcare practitioners. Furthermore, ultrasound scanners are relatively inexpensive and highly mobile, and there has never been reported any side effects from ultrasound at the intensity levels used for medical ultrasound scanning.

A conventional ultrasound image is produced by a number of adjacent ultrasound beams, emitted and received consecutively by the transducer. The transducer signals are dynamically focused during receive processing, but only a single focus is possible during transmission. This can be alleviated by compound imaging using different focal positions in transmit. The drawback is that the frame rate is reduced by the number of transmit foci. To obtain a high resolution image the conventional way, the scanner has to collect and process information from a high number of ultrasound beams. This procedure is time consuming, and generation of high resolution images, is therefore performed at the expense of the frame rate. This generates problems; since it is not possible do make a dynamic high-resolution examination of e.g. the beating heart, a moving joint, or in an acute situation where the patient cannot cooperate fully.

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One way to obtain both high resolution and high frame rate is to apply synthetic aperture technique. The basic idea of this technique is to synthesize a larger aperture than physically available, by stepwise moving a smaller active aperture through the transducers complete array. For each step a low resolution image is generated, and these are then summarized to create a high resolution image with focus at all depths, high contrast, and lower tendency to create artifacts.

There are several different ways to implement synthetic aperture imaging. The most simple version uses one array element at the time for both transmitting and receiving[1], and the most demanding versions use one or a small group of array elements for transmitting and all of the elements for receiving (full synthetic aperture)[2,3]. To implement the latter versions, the scanner must have minimum one channel for each element in the array, and be able to control all of these channels individually. Due to the desire to implement and test the technique on a conventional scanner, the consequent limitations necessitate the implementation of synthetic aperture as multi element synthetic aperture focusing[4] for this study. In this version a group of elements transmits and receives simultaneously, see Fig. 1.

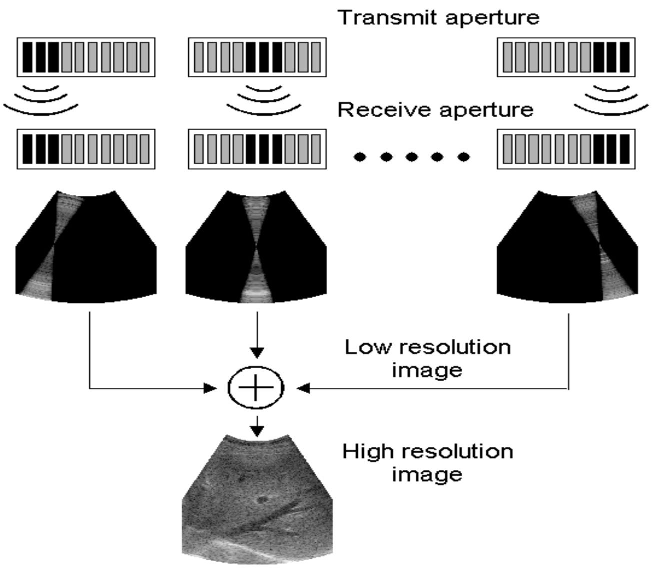

Fig. 1. Schematic illustration of SASB imaging. The ultrasound wave is transmitted from a group of elements, and the echoes are recorded by the same group of elements. The generated data is beamformed twice producing the low resolution images, which are finally summarized to produce the displayed high resolution image.

The disadvantage to all versions of synthetic aperture is the high system requirements, due to the high number of low resolution images the scanner has to produce and process. To overcome this problem, the concept of synthetic aperture sequential beamforming (SASB) has been introduced[5]. A dual stage procedure for beamforming, using two separate beamformers, leads to a significant data reduction. SASB has previously been tested with satisfactory result in two small preliminary studies, using both linear[5] and curved[6] array transducers. The data reduction makes it possible to immediately implement SASB in conventional ultrasound scanners, and in the future to construct e.g. a wireless ultrasound transducer.

The purpose of this study is to conduct a larger and more substantial comparison of clinical ultrasound images obtained with SASB and conventional technique. The images are evaluated by physicians in terms of spatial resolution, contrast, unwanted artifacts, and penetration depth.

2. MATERIALS AND METHODS

Eighteen healthy volunteers (three females and fifteen males, age range 23-34 years, all with normal body mass index) were included after informed consent and approval by The Danish National Committee on Biomedical Research Ethics. All were scanned in supine position by an experienced physician.

2.1 Equipment and data acquisition

The scans were performed with a conventional ultrasound scanner (2202 Pro Focus, BK Medical, Herlev, Denmark) equipped with a research interface and an abdominal 3.5 MHz 3.5CL192-3ML curved array transducer (Sound Technology Inc., Pennsylvania, USA). The ultrasound scanner was connected to a standard PC through the research interface. With this setup[6,7], images generated with SASB and conventional technique were recorded interleaved, i.e. one frame generated with SASB followed one frame generated with the conventional technique. This way, images from the same anatomical location were recorded almost simultaneously with both techniques, and ideal sequences for comparison were generated. The scan depth was set to 14.6 cm and the frame rate was set to five frames/s. Sequences of three seconds were recorded. The volunteers were each scanned in five different abdominal locations. The physician recorded two sequences of the left, middle and right hepatic veins and their entry in the inferior caval vein, one sequence of the liver alongside the right kidney, and one sequence of each kidney by itself. A total of 90 sequences were recorded, six of these recordings had to be left out, due to technical or patient related causes. Fig. 2 illustrates the scan locations, and shows examples of B-mode images from each location generated with the conventional technique and SASB.

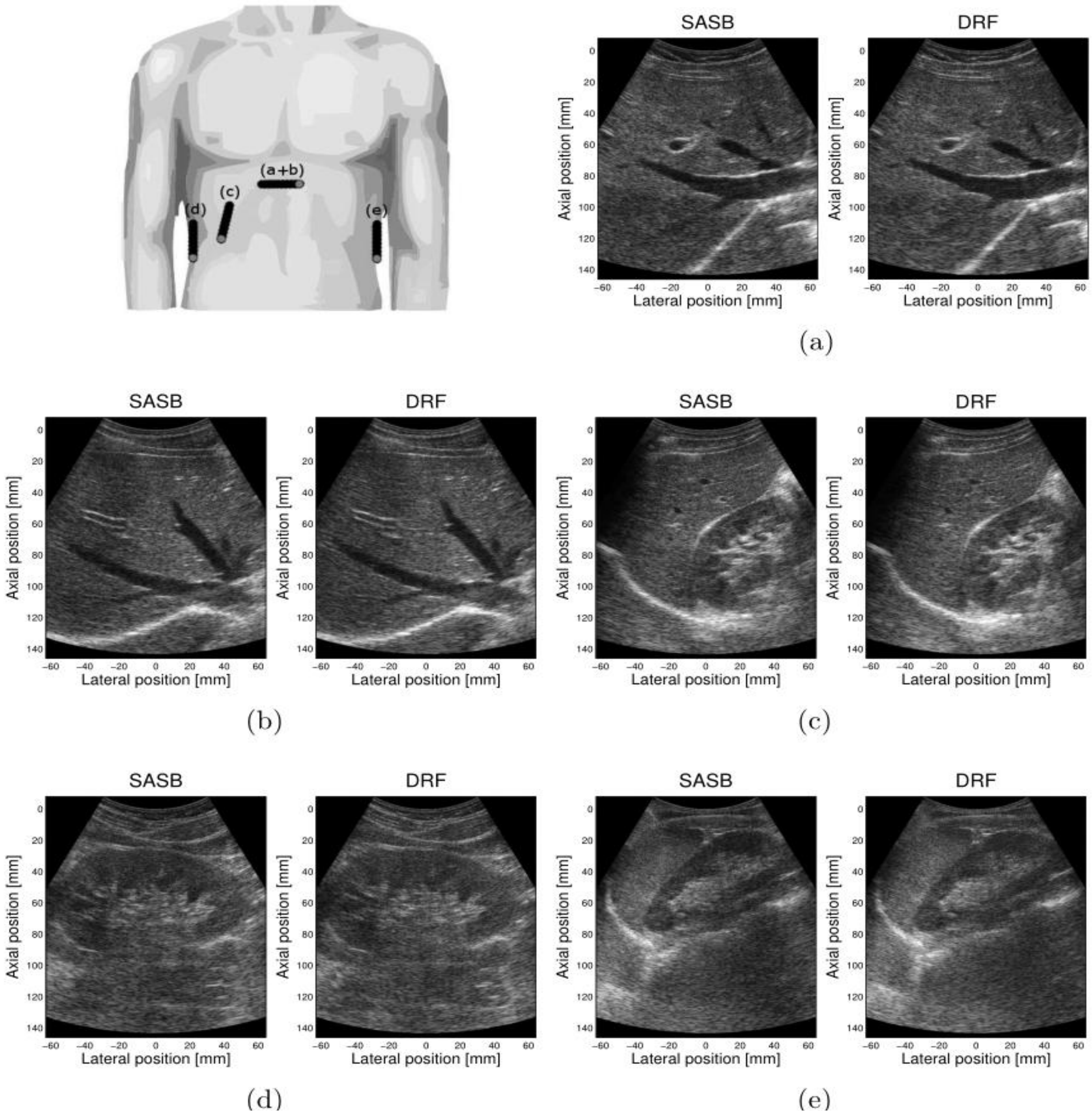

Fig. 2. The torso is illustrating the scan locations. The images show (a) transverse scanning of the liver, (b) transverse scanning of the liver using different angulation of the transducer, (c) longitudinal scanning of the right kidney with adjacent liver, (d) longitudinal scanning of the right kidney, (e) longitudinal scanning of the left kidney with adjacent spleen.

The data generated with the conventional technique were beamformed by the Pro Focus ultrasound scanner, and recorded on the PC via the research interface. The first beamforming of the data generated with SASB were performed by the Pro Focus scanner, and the data were then extracted to the PC. Using MATLAB (MathWorks Inc., Natick, MA, USA) and the beamformation toolbox BFT3[8] the second beamforming were performed off-line on the PC. All recorded data were automatically TGC corrected in order to obtain homogeneous images for the comparison. Palindromic sequences of three seconds were generated to avoid temporal discontinuities.

Prior to the actual scans, the acoustic outputs of the ultrasound scanner were measured for safety reasons. The intensity levels are listed in Table 1, and are considerably lower than the FDA limits for abdominal ultrasound scanning[9].

	FDA limits	Conventional	SASB
$I_{SPTA.3}$ (mW/cm^2)	94	0.21	0.66
$I_{SPPA.3}$ (W/cm^2)	190	28.49	69.74
MI	1.9	0.51	0.80

Table 1. Measured and calculated (MI) intensity levels alongside the FDA limits.

2.2 Image evaluation

Five physicians (radiologists) used to working with ultrasound, were asked to evaluate the sequences. None of the five physicians had knowledge about synthetic aperture imaging or seen any of the sequences before. Each physician sat isolated during the evaluation, and was not allowed to discuss the sequences until all had finished. The evaluation consisted of two parts. The first part was an assessment of image quality in terms of spatial resolution, contrast, and unwanted artifacts, and the second part was an assessment of penetration depth.

The first part was made as a double blinded, side-by-side comparison of matching sequence pairs in random order. Each sequence pair consisted of identical images recorded with the two different techniques and displayed side-by-side. This way, the physicians could evaluate the two techniques, by directly comparing two ultrasound sequences, displaying the same anatomical location. During the evaluation it was possible to view the sequences in real-time and as single frames, one step at the time both forward and backward. All 84 sequence pairs were displayed twice with different left-right placement, in order to avoid any bias related to uneven monitor quality, preferred side by the viewer, light distribution in the office, etc. A total of 168 sequence pairs were therefore evaluated by the five physicians, resulting in 840 evaluations. The actual assessment of the image quality was performed with a sliding bar underneath the sequences (Fig. 3a). If the bar was left in the middle, the evaluating physician found no difference between the sequences; otherwise the physician would draw the bar towards the side with the best image quality. How far to the side the bar was drawn, corresponded to what degree the sequence was better than the other.

The second part of the evaluation was performed as a blinded single presentation of the sequences in random order, where each physician assessed to what depth the details in the image were useful (Fig. 3b). This was done with a sliding bar from top to bottom, where the bar would be left at the level where the resolution was no longer reliable for clinical use. All parts of the evaluation process were handled using the program IQap[6].

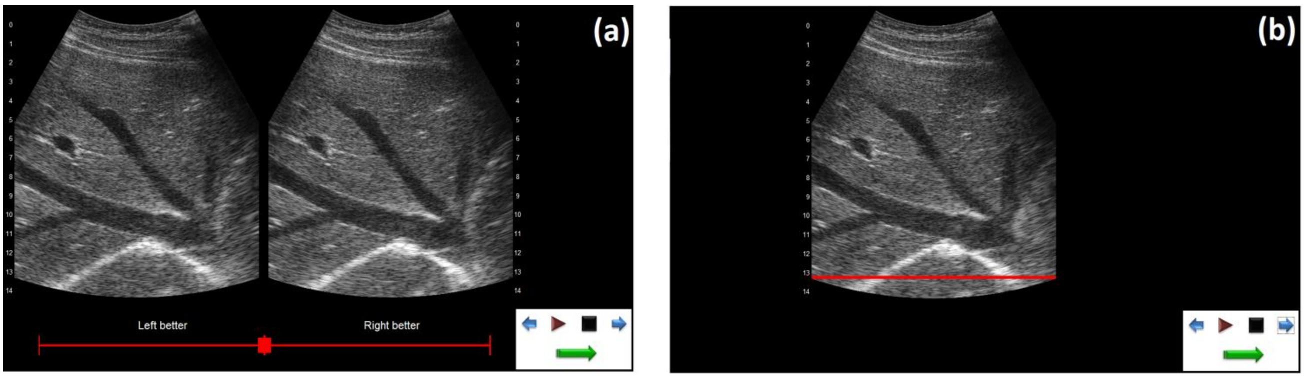

Fig. 3. Screen shots from the evaluation software. In the lower right corner the sequence controls are seen. (a) shows an example of the image quality evaluation. The sliding bar used for the actual evaluation is positioned in the bottom of the image. (b) shows an example of the penetration depth evaluation. The sliding bar used for the actual evaluation is shown across the bottom of the image.

2.3 Statistical analysis

The results of the evaluations were analyzed by a mixed effect linear model with a random effect for each sequence pair and each physician, thereby accounting for the dependence induced by repeatedly scoring the same sequence pair and collecting multiple scores from the same physician. The parameter of interest is the intercept, which captures the average score and will be negative if SASB is preferred to conventional technique. The use of the mixed effect model is solely to account for dependencies induced by sequence pair and physician and thereby providing a valid confidence interval for the intercept. In addition non-parametric test was employed as a robustness check.

3. RESULTS

All of the recorded sequences, both SASB and conventional technique, were representative and useful for clinical medical ultrasound scanning.

3.1 Image quality

There was no significant difference between the left-right and right-left evaluations, meaning that it did not matter on what side of the monitor, either of the two techniques were presented. This covariate was therefore left out. Of the 840 image quality evaluations 614 (73 %) favored SASB, 117 (14 %) favored conventional imaging, and 109 (13 %) were rated equal. The average image quality evaluation was found to be significantly negative (*p*-value: 0.0005) with a score of -3.5 (95 % CI: -5.5; -1.5). The scale ranges from -50 to 50, where negative values favor SASB. (Fig. 4)

Based on the results, a probability of 70 % was calculated for a new physician to prefer SASB over conventional technique, if a new sequence was recorded and evaluated.

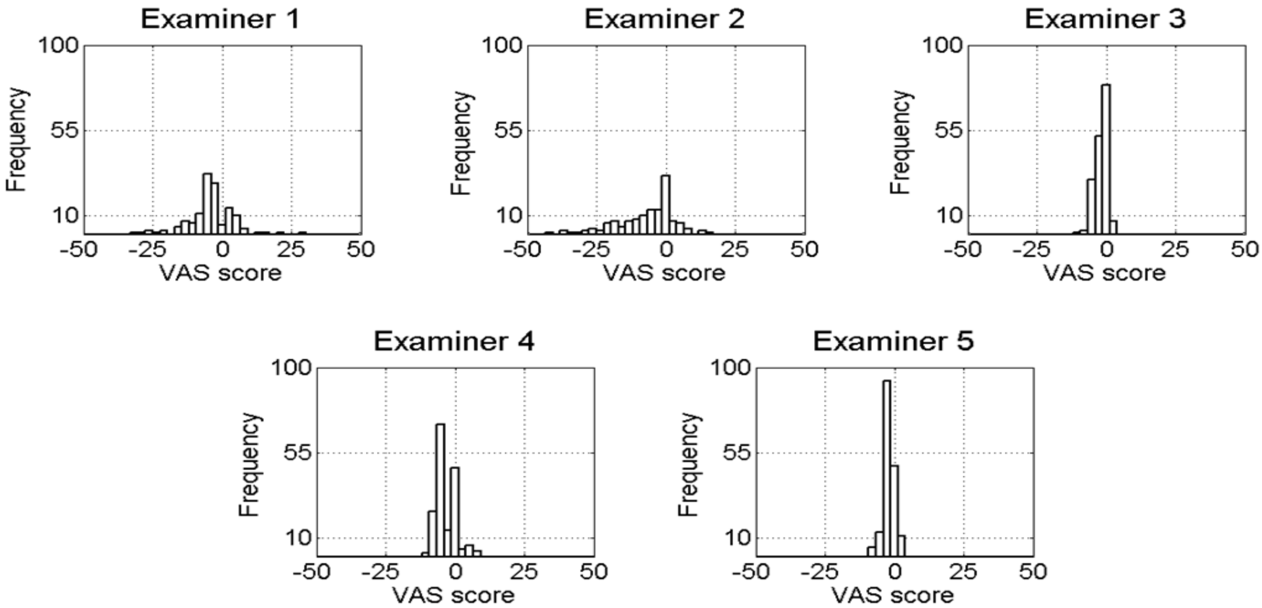

Fig. 4. Distribution of pooled answers from each radiologist's evaluation of image quality. Negative values favor SASB.

3.2 Penetration depth

The average penetration difference was found to be 0.37 mm (95 % CI: -0.83; 1.6 mm) and statistically insignificant (*p*-value: 0.55). See Fig. 5.

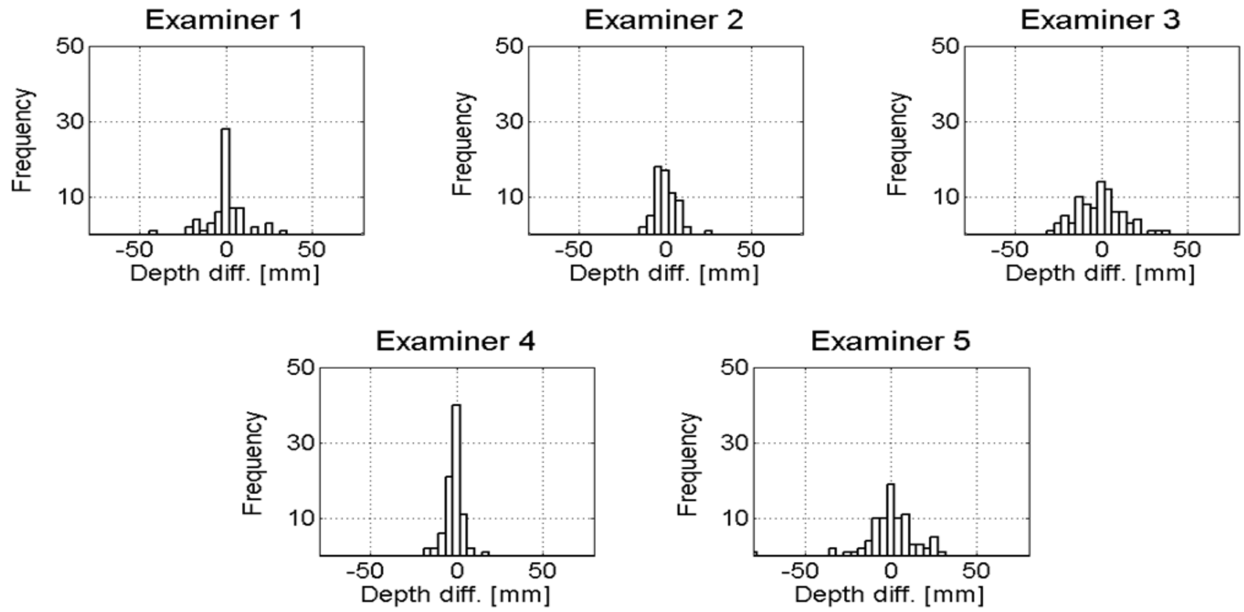

Fig. 5. Distribution of pooled answers from each radiologist's evaluation of penetration depth. Negative values favor SASB.

4. DISCUSSION

The results show that SASB is useful for clinical medical ultrasound scanning. The penetration depth is the same for both techniques, and therefore not a limitation. The image quality is found to be superior to the conventional technique by five ultrasound specialists. The reason radiologists were chosen to perform the evaluation, is they know exactly what to look for in an ultrasound image, and do this many times during a working day. Other professions would be able to provide their subjective opinion about the quality of the recorded sequences, but would not be able to tell e.g. the difference between useful or disturbing artifacts, or in which part of the image, it is relevant to evaluate the contrast and resolution. The quality improvement is however limited, but the major benefit of SASB is the substantial data reduction obtained by the sequential beamforming. This makes SASB applicable as a central element in the development of a wireless transducer. Furthermore SASB is implementable on commercial ultrasound scanners with small modifications, and is therefore a technique which is relatively accessible for further development towards working with full synthetic aperture, and gaining all the advantages of even better image quality, frame rate, and penetration.

5. CONCLUSION

Ultrasound imaging using SASB has successfully been demonstrated in a clinical trial. The technique has been evaluated by five radiologists, and shown to be superior to conventional ultrasound imaging in terms of image quality, and equal in terms of tissue penetration. If a new radiologist, unfamiliar to this study and SASB, should evaluate a new ultrasound sequence, there is a 70 % probability that he or she would prefer SASB over conventional imaging. Besides the image quality improvement, the major advantage of SASB is the massive data reduction, providing several options for future research within the field.

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